

Chemical evolution of star clusters

BY JACCO TH. VAN LOON

Lennard–Jones Laboratories, Keele University, Staffordshire ST5 5BG, UK

I discuss the chemical evolution of star clusters, with emphasis on old globular clusters, in relation to their formation histories. Globular clusters clearly formed in a complex fashion, under markedly different conditions from any younger clusters presently known. Those special conditions must be linked to the early formation epoch of the Galaxy and must not have occurred since. While a link to the formation of globular clusters in dwarf galaxies has been suggested, present-day dwarf galaxies are not representative of the gravitational potential wells within which the globular clusters formed. Instead, a formation deep within the proto-Galaxy or within dark-matter minihaloes might be favoured. Not all globular clusters may have formed and evolved similarly. In particular, we may need to distinguish Galactic halo from Galactic bulge clusters.

Keywords: stars: abundances; stars: evolution; Galaxy: evolution; Galaxy: formation; globular clusters: general; open clusters and associations: general

1. Prologue

Clusters of stars are ideal witnesses of past star formation and chemical evolution. This is because the stars in a cluster outline a sequence in photometric diagrams which can be compared with theoretical models for stellar evolution to infer an age and metallicity for the cluster. This way, young (< 100 Myr) clusters can be used to investigate the mechanisms of triggering and propagation of star formation in detail and the dependence of star formation on local environmental conditions. Intermediate-age (≈ 0.1 – 10 Gyr) clusters trace much of the history of galaxies, while old (> 10 Gyr) globular clusters (GCs) probe the formation epoch of galaxies. The ‘chemical’ (really: ‘elemental’) composition of a cluster is a powerful legacy of the entire history of star formation, stellar evolution, dynamical and interstellar medium (ISM) processes pre-dating the formation of the cluster. The cluster age tags this imprint to a specific time in the history of a galactic system.

Complications arise from the fact that the position and kinematics of a cluster may no longer be directly connected to its place of origin and birth kinematics. In the Milky Way, dynamical heating leads to outward migration away from the disc midplane and the Galactic Centre. Clusters dissolve over time, and those that survive for many billions of years generally have masses around 10^4 – $10^6 M_{\odot}$. Their formation requires conditions which are uncommon in the present, nearby Universe. In addition, attempts to quantify the star-formation rate are hampered by the uncertain relationship between the conditions under which stars were formed and the number and size of clusters which were produced. Nevertheless, their chemical composition can constrain all of these open issues.

I concentrate on new lines of evidence, emerging in a fast-paced field of research, complementing and complemented by the excellent reviews of Gratton *et al.* (2004) and Friel (1995), Freeman & Bland-Hawthorn (2002) and Brodie & Strader (2006).

2. The agents of chemical evolution

We must first define what we mean by metallicity. In astrophysics, metals are elements heavier than hydrogen (H), helium (He), lithium (Li) and beryllium (Be). The metallicity is the fraction, in mass, in all these elements combined. This amounts to at most $Z \approx 0.05$, is $Z_{\odot} \approx 0.02$ for the Sun, and can be as little as $Z \approx 0.0001$ in the most metal-deficient Galactic GCs (and less still in extremely metal-deficient halo field stars). In most main-sequence (MS) stars, He takes up $Y \approx 0.25$ of the total, with the remaining $X \approx 0.7$ in H (where $X + Y + Z = 1$). Many metals are very rare and make a negligible contribution to the total. It would be cumbersome and inaccurate to have to measure the abundances of individual metals and add them all up to arrive at a value for Z . It is therefore sensible to pick one metal and use that as a proxy for metallicity. Often, iron (Fe) is used, relative to that of H and benchmarked against the Sun, denoted as $[\text{Fe}/\text{H}]$. Fe is common, and its production in supernovae (SNe) results in a steady increase over time as subsequent generations of stars incorporate the accumulated enrichment by the previous generations. This scenario may, in fact, be traced more promptly by oxygen (O), which is even more common and relatively easily measured in the ISM of other galaxies. Yet, different histories will lead to different relative enhancements (or even depletion) of the various elements, including O and Fe, so there really exists no true single chemical yardstick.

(a) *The origin of the elements*

Elements heavier than H are synthesized both in stars and in explosions. Differences in yields are generally associated with the temperature or neutron density at which nuclear synthesis takes place. But to speak of a yield in terms of chemical enrichment of the Universe, the products must leave the gravitational boundary of their source. In stars, this requires a mechanism of transport through the mantle into the surface layers, followed by mass loss. In explosive events, it requires that the products join the ejecta instead of being encapsulated within a compact remnant (neutron star, NS, or black hole). The yields from stars generally depend on other parameters in addition to mass and composition, for instance rotation and magnetic fields, which both affect the production rates and mixing efficiencies and possibly also the mass-loss rate. The physics of mixing and mass loss are not fully understood, and are only incorporated in stellar models in an ad hoc, parameterized way. And some crucial reaction rates are uncertain by more than an order of magnitude.

The lifetime of a star is roughly also the delay timescale between its formation and its contribution to chemical enrichment of the ISM. Chemical enrichment of subsequent generations of stars is further delayed between injection into the ISM and participation in star formation. Table 1 gives a succinct overview of the main protagonists, the (minimum) timescales on which they operate and the key contributions they make to chemical enrichment.

Table 1. *Factories of the elements*

Source	Birth mass (M_{\odot})	Timescale	Key elements
Massive stars	> 20	2–10 Myr	He, N (rotating, or Wolf–Rayet-type)
SN II	8–20	10–40 Myr	He, CNO, Fe, Si, Ca, r-process
AGB (HBB)	4–8	40–200 Myr	N, He, Na, s-process
SN Ia	1–8 ?	\sim Gyr	Fe, Cu
AGB (C)	1.5–4	0.2–2 Gyr	C, F, s-process
RGB	0.8–1.5	2–12 Gyr	^{13}C , ^{14}N

AGB: asymptotic giant branch, HBB: hot-bottom burning, RGB: red-giant branch.

(i) *Fe-peak elements*

These elements, with atomic masses near that of Fe, are ejected in SNe. In particular the presence of nickel (Ni) is a tell-tale signature of such events, with ^{56}Ni the product of the final nuclear burning stage (that of silicon, Si, by α capture) in massive stars ($> 8 M_{\odot}$). The decay of ^{56}Ni to the cobalt isotope ^{56}Co and subsequently to ^{56}Fe creates much of the Fe released in SNe. In Type II SNe, much of the Ni and Fe is locked up in the collapsing core, but very massive ($> 130 M_{\odot}$) metal-poor stars explode entirely as a result of pair creation, leaving no remnant. Fe is also produced in large quantities in explosive nucleosynthesis in Type Ia SNe, which are devoid of H as they are detonations or deflagrations of white dwarfs (WDs). All this Fe ends up in the ISM. Because WDs are the products of intermediate-mass stars ($0.5\text{--}8 M_{\odot}$), enrichment by SNe Ia is slower ($10^8\text{--}10^9$ yr; Raskin *et al.* 2009) than that by SNe from massive stars. A Type Ia SN likely results from the WD having grown to the Chandrasekhar mass limit ($1.4 M_{\odot}$) by accreting matter from a companion star, or from the merger of two WDs. This additional delay is very uncertain: massive WD progenitors leave WDs with masses closer to the Chandrasekhar limit, but the mutual separation of the mass donor and receiving WD (or of the two WDs), and hence the efficiency of mass transfer (or orbital degradation), may also depend on the birth mass.

The net result is that the Galactic disc grew to $[\text{Fe}/\text{H}] \approx -1$ dex through SNe from massive stars, after which Type Ia SNe kicked in on a typical delay timescale of \sim Gyr. Subsequently, the continued increase in Fe content diluted earlier enrichment from massive stars in other elements (‘Q’), decreasing their $[\text{Q}/\text{Fe}]$ ratios towards zero (solar). Copper (Cu) and manganese (Mn) are produced more lavishly in Type Ia SNe. Hence, they are underabundant with respect to scaled-solar abundances by 0.3–0.7 dex at $[\text{Fe}/\text{H}] < -1$ dex, and only reach solar values after prolonged enrichment by Type Ia SNe. Other Fe-peak elements are titanium (Ti), which is easy to measure in stellar spectra, and vanadium (V), which forms easily recognizable molecules in the atmospheres of the coolest M-type giant stars, and chromium (Cr).

(ii) *The r-process*

Heavy elements are produced by neutron (n) capture, starting with Fe (the ‘seed’ nucleus). This proceeds rapidly in the explosive deaths of massive stars, and anything as massive as uranium (U) can result. An excellent tracer of this process is europium (Eu). Indeed, in the Galaxy, $[\text{Eu}/\text{Fe}] \approx 0.4$ dex up to $[\text{Fe}/\text{H}] \approx -1$ dex, after which it decreases towards solar values, essentially showing the opposite behaviour is produced through α capture. C (and s-process elements) is transported

to the surface as the convective envelope penetrates the production site as a result of the switch between H- and He-shell burning (thermal pulsing, TP). In subsolar-metallicity stars, this turns the star into a C star as the surface C/O ratio exceeds unity. In massive AGB stars (4–8 M_{\odot}), the bottom of the convection zone is so hot that an incomplete CNO cycle operates (hot-bottom burning: HBB): C is converted into N, but not subsequently into O. These stars produce N and deplete C. Isotopic changes occur too: for instance, ^{18}O is depleted and the $^{12}\text{C}/^{13}\text{C}$ ratio is reduced. Na, aluminium (Al) and Mg can be synthesized as well *through* p-capture, especially at ever lower metallicities: at very low metallicities, $Z \sim 10^{-4}$, in the most massive AGB stars, O is more fully depleted than C, and these stars become C stars even though they do not enrich the Universe with C but instead with large amounts of N (Ventura & D’Antona 2009).

(iii) *Helium*

He is produced in all stars $> 0.5 M_{\odot}$, but it does not necessarily end up in the ISM. One would expect massive AGB stars undergoing HBB to yield He. Super-AGB stars, which behave like AGB stars but proceed to burn C in the core, contribute He as well as enhancing C+N+O (Pumo *et al.* 2008). Their fate as either ONe WD or electron-capture SN is unclear. Prolific producers are Wolf–Rayet (WR) stars. These have shed their H envelope as a result of strong stellar winds in their previous phase as an O- or B-type supergiant or possibly after an intermediate phase as a red supergiant (RSG). Their surface layers consist predominantly of He, with either abundant N (WN; $20 < M < 40 M_{\odot}$) or C and O (WC; $> 40 M_{\odot}$). WR stars also have strong winds and thus enrich the ISM with He, as well as N, or C and O. Note, however, that if one adds up the lost H, one arrives at more similar enrichments to those contributed by SNe of Type II ($8 < M < 20 M_{\odot}$).

(iv) *Fluorine*

Intermediate in mass between O and Ne, fluorine (F) is produced in the OF-cycle variant of the CNO cycle, most likely in intermediate-mass TP–AGB stars, as it is destroyed in more massive stars (Lebzelter *et al.* 2008; Abia *et al.* 2009).

(b) *Internal chemical evolution*

Care must be taken not to mistake internal chemical processes, happening within the cluster since its formation, for primordial enrichment. This is a prime concern in old clusters, where the evolved giant stars are so much brighter and hence more readily accessible to spectroscopic investigation than their MS siblings. Such interfering processes can be internal to the star itself, or internal to the cluster but external to the star in question.

(i) *Surface abundances affected by stellar evolution*

In cool giants, ‘mixing’ is due to convection, the mode of energy transport from the nuclear production site to the photosphere. Normally, a radiative layer exists between the nuclear burning site and the convective mantle, acting as a buffer. But occasionally, restructuring of the mantle as a consequence of switching nuclear

furnace allows the convection zone to penetrate, leading to a ‘dredge-up’ episode. Of particular intensity, the third dredge up occurs repeatedly (briefly, with intervals of typically 10^4 yr) during the TP–AGB phase. This brings C and s-process elements to the surface, creating a C star (or an S-type star which has $C/O \approx 1$ and is thus rare) or a N-enriched star if HBB operates. It is accompanied by short-lived elements such as technetium (Tc), so if Tc is seen then the surface enrichment is recent. Especially in metal-poor intermediate-mass stars, the C/O ratio on the surface is easily reverted from O to C dominated. Because the molecular chemistry of the atmospheres of cool stars ($T < 4000$ K) is largely determined by whatever element is left after formation of carbon monoxide (CO), C stars look very different from O-rich red giants, displaying strong C_2 and TiO bands, respectively. In cool stars with $C/O < 1$, carbonaceous molecules are still present, most notably CH (observable as, e.g., the ‘G band’ at 4300 Å) and CN (e.g., around 3800 Å).

In low-mass stars ($< 1.5 M_{\odot}$), during their ascent of the red-giant branch (RGB), CNO-cycle burning in the H shell can drive CNO isotopes to their equilibrium values, which are very different from their primordial levels: $^{12}C/^{13}C \rightarrow 3.5$ (during AGB H-shell burning this ratio is typically around 15–20, with a solar value of ≈ 90) and ^{14}N and ^{17}O become abundant isotopes. The first dredge up on the RGB is not sufficiently efficient and perhaps absent in metal-poor stars. A non-canonical mixing mechanism must be operating above the RGB ‘bump’ (around $M_V \approx 0$ mag, caused by a discontinuity in the molecular weight). Rotation, or the thermohaline effect (a molecular-weight inversion causing buoyancy; Eggleton *et al.* 2006; Charbonnel & Zahn 2007), have been suggested as its origin. Whatever its cause, it must be more effective at lower metallicity, as $^{12}C/^{13}C$ ratios close to the equilibrium value are observed in metal-poor, luminous RGB stars, $[Fe/H] < -0.8$ dex, but not in their more metal-rich counterparts (Charbonnel & Do Nascimento 1998).

Li is normally depleted during the first dredge-up episode: Pasquini *et al.* (2005; in NGC 6752) and Bonifacio *et al.* (2007; in 47 Tuc) provide evidence for a Li–Na anticorrelation, consistent with the admixture of gas depleted in Li and rich in Na produced by p-capture reactions. However, the anticorrelation appears in GCs but not in the field, and may thus result from the GC formation mechanism. The Galactic GC NGC 6397, on the other hand, exhibits a uniform Li content across its unevolved population. Rare super-Li-rich stars have been found, too, and some unconventional process is required to explain this happening some way up the RGB (Abia *et al.* 1991). Li enhancement in Galactic massive AGB stars does not appear to be accompanied by s-process enhancement (García-Hernández *et al.* 2007), while in the Magellanic Clouds it is (Smith *et al.* 1995): a metallicity effect.

In stars with radiative mantles, other effects can cause modification of the surface chemical abundances. In horizontal-branch (HB) stars (post-RGB, core-He burning giants) gravitational settling and selective radiative levitation can lead to differentiation of metals, making these stars highly unsuitable for studying primordial enrichment or even later enrichment by external processes. This is a pity as, for instance, He lines are visible in the spectrum of stars in this temperature regime ($T > 11\,500$ K). More stars of spectral type A display peculiarities (‘Ap’ stars), some believed to be due to the acting of magnetic fields (metallic, ‘Am’ stars).

Fast rotation may also induce mixing of the star where it would otherwise not be expected. This might produce hot stars with a surface enriched in N, as well as

C and O. This contributes to the uncertainty about the main producers of N in the early Universe: rotating massive stars (Decressin *et al.* 2007) or perhaps massive AGB stars (Ventura & D’Antona 2009)?

Finally, surface chemical abundances may undergo dramatic changes as the star sheds its H-rich mantle, directly exposing the layers underneath in which nuclear burning had taken place previously. This gives rise, for instance, to post-AGB objects enriched in s-process elements. Or massive WR stars, which are easily recognized by their very broad emission lines (no absorption lines at all). The presence of WR stars in a cluster is related to the cluster’s age, but may be affected by additional properties of the stars such as their metallicity at birth and rotation rate. Similarly, C stars in a cluster help constrain its age.

(ii) *Accretion*

In dense stellar systems, external pollution by other stars may be relatively important: accretion from a pool of gas, possibly replenished by the winds from other stars, or mass transfer from binary companions, or *through* stellar mergers.

In a standard Bondi–Hoyle–Lyttleton scenario, the accretion rate from diffuse gas is remarkably well approximated by

$$\dot{M} = \frac{4\pi G^2 M^2 \rho}{(c_s + v)^3}, \quad (2.1)$$

where M is the mass of the accreting star, ρ the density of the medium it passes through, and c_s and v are the sound and bulk speed, respectively. In 10 Gyr, a star of $M = 1 M_\odot$ moving through ISM of $\rho = 2 \times 10^{-24} \text{ g cm}^{-3}$ ($\approx 1 \text{ particle cm}^{-3}$) and $c_s = 10 \text{ km s}^{-1}$ at $v = 10 \text{ km s}^{-1}$ will accrete just $\Delta M \approx 1 \times 10^{-5} M_\odot$. Denser gas has not been found in GCs (Freire *et al.* 2001; van Loon *et al.* 2009). Kinematically colder populations, with $v \sim 1 \text{ km s}^{-1}$ only accrete more efficiently from thermodynamically cold gas ($c_s \ll 10 \text{ km s}^{-1}$). In any case, one would expect all stars to participate in this process and become polluted. Thus, accretion from diffuse gas to explain abundance anomalies in GCs seems a rather contrived scenario.

Binary mass transfer is observed in a number of types of systems. If a MS star accretes mass from the mantle or wind from a C-star red-giant companion, the chemical imprint upon the radiative layers of the MS star is obvious: the MS star turns into a C star as well, at least in appearance, along with the usual s-process signatures such as Ba enhancement. This naturally explains the observations of C stars in GCs which are too faint for TPs and the third dredge up to operate, although it is more challenging to explain such C and Ba stars found at the tip of the RGB, where the convective mantle would mix and dilute the accreted C with oxygenous material (van Loon *et al.* 2007). To prove that these kinds of enrichments are neither due to binary mass transfer nor to internal nucleosynthesis and mixing, a consistent pattern must be found along the RGB and preferably also on the MS.

Stellar mergers may result from common-envelope systems in which a binary star becomes enveloped by the red-giant mantle of one of the components as it ascends the RGB. If the cores merge, a more massive star may remain, at a position on the MS higher than the MS turnoff associated with the evolution of single stars

in a coeval population. These ‘blue stragglers’ could be mistaken for a younger population, but the absence of corresponding stars at more evolved stages of evolution rules out this possibility.

(c) *Material, chemical, radiative and mechanical feedback*

The total amount of mass lost by a star is reasonably well known (see also Kalirai & Richer 2010). But the exact timing of the mass loss determines the ultimate yields (the initial mass function, IMF, determines the combined yield), while the wind speed and momentum determine the degree and timescale of mixing with the surrounding ISM (this also depends on the gravitational field and ISM density).

AGB stars lose mass through slow winds, $\sim 10\text{--}20 \text{ km s}^{-1}$ (lower speeds at lower metallicity) and metallicity-independent mass-loss rates of $\sim 10^{-7}$ to $10^{-4} M_{\odot} \text{ yr}^{-1}$ (van Loon 2006). These winds are easily retained within massive GCs, but may escape from clusters lacking sufficient mass (be it baryonic or dark). RSG winds are relatively slow too ($< 40 \text{ km s}^{-1}$). Stars of $> 30\text{--}40 M_{\odot}$ do not reach the RSG phase. These O- and B-type supergiants, and WR stars, or similar kinds of progenitors or descendants of RSGs, have much faster winds ($\sim 10^3 \text{ km s}^{-1}$).

SNe have extremely fast ($\sim 10^4 \text{ km s}^{-1}$) and energetic outflows, which sweep away any gas present in their vicinity. At some distance it will run out of steam and stall, but the combined effect of several SNe creates a large cavity in the ISM. Various types of SNe are still poorly understood, for instance Types Ib/c (probably resulting from WR stars) and II-L. The fate of super-AGB stars is unknown. If they blow up they may efficiently spread their enriched material over large distances, but otherwise enrichment of the ISM takes place mainly through their slow winds.

Strong stellar winds and SNe are generally found to compress the surrounding ISM, and star formation is often seen surrounding the blown cavities. Similarly, radiative feedback from luminous, hot stars can induce a wind emanating from a star cluster, and also create an ionization front which may induce the collapse of molecular cloud material and thereby trigger star formation. Yet, convincing evidence of actual triggering of new star formation as a result of the mechanical or radiative feedback is surprisingly sparse (cf. Chu *et al.* 2005; Oliveira *et al.* 2006). The younger generation does not coincide spatially with the central cluster, and it is doubtful that the feedback and subsequent star formation (possibly from chemically enriched gas) ultimately results in a cluster with a composite population of stars.

3. Chemical evolution of star cluster systems

(a) *The Galactic population of open clusters*

The Galactic system of open clusters (OCs) is fairly well understood. Their metallicities are around solar or somewhat lower and they generally compare well to the metal-rich end of the Galactic-disc field-star population. This is expected, as OCs have ages typically less than a Gyr and thus formed from material that had been chemically enriched over many Gyr. The reason for the abundance of such relatively ‘young’ OCs is not a recent burst in their formation, but rather the dispersal of older OCs due mainly to evaporation of stars in combination with continuous dynamical relaxation, and tidal effects within the Galactic gravitational potential (see also de Grijs 2010; Larsen 2010).

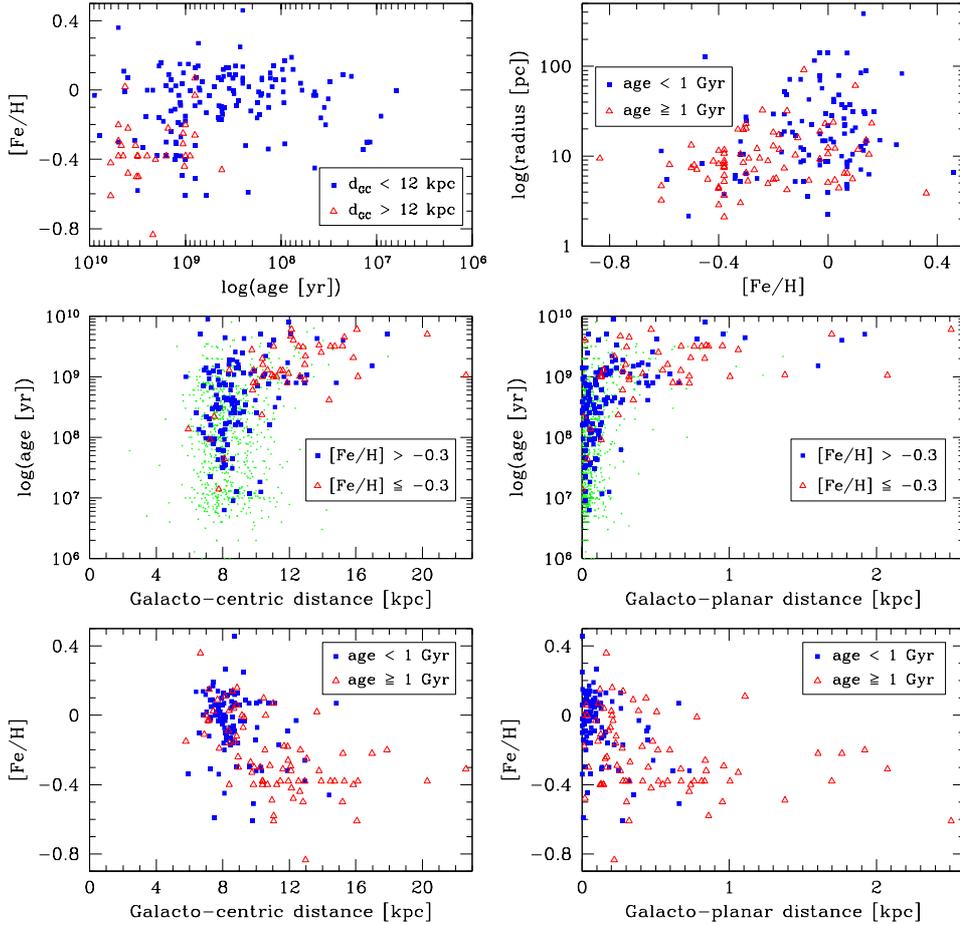


Figure 1. Trends in the global properties of 1787 Galactic open clusters from the compilation of Dias *et al.* (2002).

No age–metallicity relation is present for OCs (cf. Pancino *et al.* 2009). This is illustrated in figure 1, where slightly supersolar-metallicity OCs are seen at all ages, and the clearly subsolar-metallicity OCs of relatively old age are displaced within the Milky Way. Indeed, metallicity gradients are seen (Pancino *et al.* 2009; and references therein) with respect to Galactocentric distance and distance to the Galactic midplane, and similar gradients are seen in the cluster ages (figure 1). This is not unexpected, as clusters, like field stars, migrate away from the peak in the mass density as a result of encounters with gravitationally disturbing bodies (in the case of OCs, these are likely molecular clouds and/or spiral arms). The lack of young clusters at large Galactocentric distances suggests a lack of recent in situ star formation, with consequentially lower rates of chemical evolution, but this may be resolved by more systematic searches for young OCs outside the solar circle.

The larger OCs have close-to-solar metallicity, with metal-poor OCs—invariably older—being more compact (figure 1). This may be a selection effect, as diffuse OCs dissolve over time. Yet massive ($\sim 10^4 M_{\odot}$), young ($\sim 10^7$ yr) OCs are only found in the inner regions of the Galaxy, which suggests that their formation requires

stronger gravitational confinement of the molecular cloud environment. Examples are the well-known Arches and Quintuplet clusters and Westerlund 1, harbouring very massive stars including WR stars, and a number of recently-discovered (in infrared surveys) OCs with large populations of RSGs (Figer *et al.* 2006; Davies *et al.* 2007). They have near-solar metallicities, as expected from their age and location in the inner parts of the Galactic disc. (It is well-known that the Sun is rather metal-rich for its age of 4.6 Gyr, but also that chemical enrichment in the Galactic disc has proceeded very slowly, if at all, since the Sun's formation. A reason may be the ongoing accretion of gas of subsolar metallicity from the halo, diluting chemical enrichment.)

The massive cluster NGC 6791 (see also below) is considered an OC, but being as old and (supersolar) metal-rich as it is, and given its location in the inner Galactic disc, it is likely associated with the end of the bulge-formation epoch. Its outward migration has also been suggested by Boesgaard *et al.* (2009).

(b) *The Galactic globular cluster system*

GCs do not contain stars with $[\text{Fe}/\text{H}] < -2.3$ dex. Stars much more metal-deficient are found in the halo, so either GCs did not form at those early, metal-poor times, or they have not survived, either because they were not massive enough or because they were subjected to particularly hostile conditions early on. This means that the present-day, surviving GCs are not the first stellar systems to have formed, and that their chemical imprint is testimony of the earlier, 'lost' generation (or generations).

The Galactic GC system has long been known to be composed of two main subsystems, one associated with a halo-like distribution and kinematics, and the other with a more flattened and kinematically more ordered distribution: the latter population is referred to as a 'bulge' population. This is illustrated in figure 2, where the metallicity distribution is clearly bimodal with peaks on either side of $[\text{Fe}/\text{H}] \approx -0.9$ dex. It is interesting to note that there is no correlation whatsoever between mass (by proxy of absolute visual magnitude, M_V) and metallicity. Halo and bulge GCs are similar in mass.

A change in the HB ratio from positive, if a pronounced hot HB is present, to negative occurs among the halo GCs (figure 2). It is uniformly negative among bulge GCs. Between $[\text{Fe}/\text{H}] \approx -1.3$ and -1.8 dex, GCs are found with both negative and positive HB ratios, giving rise to the so-called 'second-parameter problem'. In fact, the metallicity at which this occurs is somewhat lower for less massive GCs (perhaps this is a bias due to the paucity of hot-HB stars). Indeed, the transition in HB ratio is abrupt for the top two magnitudes in M_V , at $[\text{Fe}/\text{H}] = -1.3$ dex. The most metal-rich GCs that show a hot HB have $[\text{Fe}/\text{H}] = -1.3$ dex even among the less massive GCs, at $M_V \approx -6$ mag.

Halo GCs extend to lower central luminosity (a proxy for mass) density than bulge GCs (figure 2). These may be dissolving but given that they have persisted for so long, a tantalizing alternative is that they contain a modest amount of dark matter (making up for the lack of *luminous* mass density). There is a trend for higher metallicity at higher central density, but this is very weak indeed. There does not appear to be any correlation between metallicity or central density on

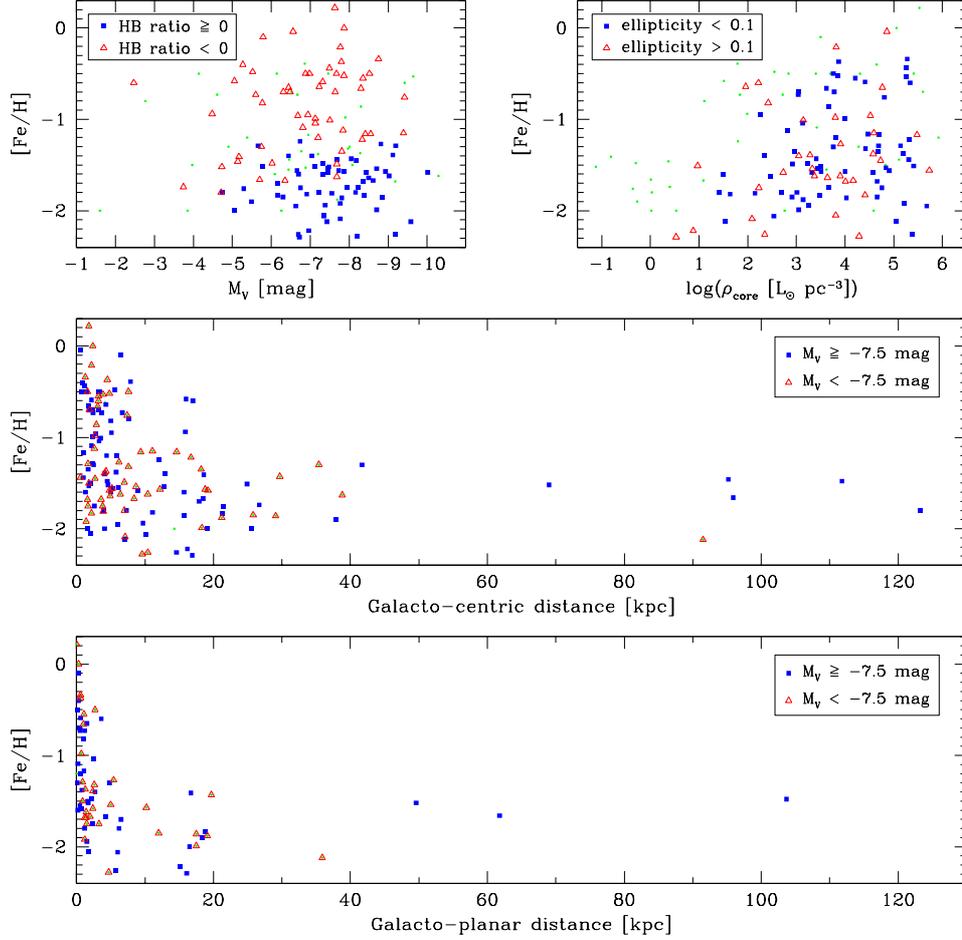


Figure 2. Trends in the global properties of 150 Galactic globular clusters from the compilation of Harris (1996).

the one hand, and ellipticity of the GC on the other, so the amount of angular momentum inherited from their formation appears to be entirely random.

The bimodal metallicity distribution is linked to the halo and bulge division. The Galactic spatial distributions indeed exhibit a sharp division, at $[Fe/H] \approx -1.3$ dex when considering Galactocentric distance or $[Fe/H] \approx -1.4$ dex in terms of Galactoplanar distance (figure 2), which, curiously, is a few dex lower than the location of the division in the metallicity distribution. The halo GCs venture to well over 100 kpc distance, while the bulge GCs stay within 20 kpc from the Galactic Centre. Both systems are flattened, with Galactoplanar distances being smaller than their Galactocentric equivalents. Especially the bulge GCs stay within just a few kpc from the Galactic plane, but halo GCs also often have orbits very close to the midplane. The less massive GCs, in both systems, are distributed more widely. This is a clear signature of mass segregation within the GC systems.

Fraix-Burnet *et al.* (2009), on the basis of a clever multivariate analysis, deduced an age-metallicity relation for the halo GCs, from $[Fe/H] \approx -2$ dex 12 Gyr ago to

$[\text{Fe}/\text{H}] \approx -1.3$ dex 9 Gyr ago. Note, however, that their data are also consistent with a more rapid increase in metallicity ≈ 10 – 11 Gyr ago, from $[\text{Fe}/\text{H}] \approx -1.9$ to -1.4 dex. This is also the age interval in which the bulge GCs seem to have appeared on stage, having generally higher metallicities— $[\text{Fe}/\text{H}] \approx -1.4$ to -0.5 dex—than halo GCs of similar age.

Fraix-Burnet *et al.* (2009) further confirmed earlier evidence that Galactic GCs differ from Local Group dwarf galaxies in having higher $[\alpha/\text{Fe}]$ ratios. Halo GCs are indistinguishable from halo field stars in this respect. Bulge GCs lack the dilution of α elements by further enrichment with Fe from Type Ia SNe that characterizes field stars in the Galactic disc. This reaffirms the notion that bulge GCs must have formed, and been chemically enriched, rapidly.

Sparse data exist for the most metal-rich GCs ($[\text{Fe}/\text{H}] > -0.5$ dex). In Liller 1, NGC 6553 and NGC 6528, $[\text{Ca}/\text{Fe}]$ is as high as for metal-poor GCs (Gratton *et al.* 2004) and thus different from field stars and OCs. There is no dependence of $[\text{Ca}/\text{Fe}]$ on Galactocentric distance. NGC 6528 is also the only metal-rich GC with measured $[\text{Mn}/\text{Fe}]$, which is also as low as that in metal-poor GCs. So, Type II SNe seem to have done the job all the way to $[\text{Fe}/\text{H}] \approx 0$ dex, where in other Galactic components (and possibly in Rup 106 and Pal 12) Type Ia SNe contributed.

Some GCs seem to defy these trends. For instance, Rup 106 and Pal 12 are both ‘young’ outer-halo GCs. For their $[\text{Fe}/\text{H}] \approx -1$ dex, they have rather low Fe-peak (Ni) and low α (Ca)-element abundances, and in the case of Rup 106 also low n-capture (Eu, Ba)-element abundances (Gratton *et al.* 2004). Possibly, they formed somewhere else at a slower rate, allowing relatively more SN Type Ia enrichment, but apparently very little by massive stars. However, their ratio of r-process and s-process element abundances appears normal, suggesting AGB stars did not play a more significant role compared to massive stars than what is normally seen.

(i) Carbon and nitrogen enhancement

It is not uncommon for cool giant stars in Galactic GCs to exhibit strong CN bands. Sometimes, a clear bimodality between CN-strong and CN-weak stars is observed (e.g., van Loon *et al.* 2007; Kayser *et al.* 2008), but all possible combinations occur. In the field, only weak CN bands occur (but CH can be strong). CN and CH are often anticorrelated, suggesting that it is N which varies, not C. The abundance peculiarities are also detected in MS stars, and the pattern persists further along the evolutionary path, so these stars must be well mixed, i.e., they have formed from enriched material not polluted on their surfaces. The bimodality suggests that some stars may have been affected by N enrichment while others were not, and the lack of this signature in field stars suggests that the enrichment is a particular feature of (Galactic) GCs.

Na correlates with (C)N, suggesting a p-capture process perhaps related to AGB stars of relatively low masses. In 47 Tuc and NGC 6752, neither Mg, Si, Ca, Fe nor Ba appeared to vary (Cottrell & Da Costa 1981), but Al also varies at medium–low metallicity and Mg also at low metallicity, so the N producers were probably slightly different, depending on their metallicity or mass, if the mass range of the polluters correlates with the GC metallicity.

The sum of C+N+O generally remains constant. Decressin *et al.* (2009) found that, as C+N+O increases in rotating massive AGB stars, nonrotating massive

AGB stars are more likely to be responsible for N enhancement in GCs, but they consider this awkward as one may expect GC stars to rotate faster, not slower, than in the field. There is also no obvious reason for a bimodality in the rotation rates, which might mean that the polluters were never part of the GC.

(ii) *The O–Na anticorrelation*

An anticorrelation between O and Na is seen in all Galactic GCs. $[\text{O}/\text{Fe}]$ can vary within an order of magnitude, roughly around $[\text{O}/\text{Fe}] \approx 0$ dex. For $[\text{O}/\text{Fe}] < 0$ dex, $[\text{Na}/\text{Fe}] \approx 0.4$ dex, but there is a huge spread down to $[\text{Na}/\text{Fe}] \approx -0.3$ dex for $[\text{O}/\text{Fe}] > 0$ dex. The explanation for the O–Na anticorrelation is the production of Na in the CNO cycle, and in associated cycles at higher temperatures (involving, progressively, Ne, Mg and Al). These cycles occur in low-mass stars (H shell) as well as intermediate-mass stars (HBB), so they can give rise to evolutionary as well as primordial enrichment: MS-star abundances can differentiate between these scenarios. Rotating massive stars can also produce Na, Al and N enhancement (Decressin *et al.* 2007).

(iii) *Helium*

He is hard to study spectroscopically, but it has dramatic photometric effects: for instance, He-rich HB stars will be bluer. In hot-H burning, He may be correlated with Na and with O depletion. In that case, one would expect stars on the blue HB to be Na-rich and O-poor, and vice versa for stars on the red part of the HB. Gratton *et al.* (2004) found that while $[\text{Fe}/\text{H}]$ is higher for hot ($T > 11\,500$ K) HB stars, $[\text{He}/\text{H}]$ is in fact lower. Villanova *et al.* (2009) found a homogeneous $Y \approx 0.25$ for stars in the ‘safe’ range $8500 < T < 11\,500$ K, and Catelan *et al.* (2009) ruled out He enhancement to explain the HB morphology in the Galactic GC M3.

(c) *The formation of the Galactic globular clusters*

The Galaxy’s baryonic halo only contains $\sim 10^9 M_\odot$, of which less than a tenth is contained in globular clusters. This is only $\sim 1\%$ of the total baryonic mass in the Galaxy. So, there may not have been more than $10^{10} M_\odot$ of gas involved in forming it, roughly the amount of gas currently present in the disc. If we spread this over a volume of, say, $10 \times 10 \times 10 \text{ kpc}^3$, we get a density of 3 particles cm^{-3} , similar to that in the disc and to the atomic–molecular transition in the diffuse ISM. One could therefore imagine to form a ‘halo’ by instabilities in the diffuse ISM creating molecular clouds. However, ‘giant’ molecular clouds like those in the disc do not form GCs. In any case, a density gradient would be established quickly, concentrating gas into the inner portions of the hypothetical volume. It is thus attractive to form both the halo and bulge field and GC populations in the central regions of the proto-Galaxy, where ‘hyper’ molecular clouds, an order of magnitude larger and denser than giant molecular clouds, might have formed.

Concentrating star formation within a small volume naturally explains a fast and global enrichment, dominated by massive stars, leading to the observed halo GC age–metallicity relation (Fraix–Burnet *et al.* 2009) starting from $[\text{Fe}/\text{H}] \sim -2.3$ dex. M15 is one of the most metal-poor GCs and unique among these in also showing

large star-to-star variations in r-process elements (at constant r/s). Perhaps M15 was one of the first GCs to have formed, when conditions were changing fast.

Stellar feedback, possibly in combination with an active galactic nucleus outflow, would have driven gas into intergalactic space. Star-formation efficiencies rarely reach 20%, but are often considerably lower. Feedback processes resulting from the star-formation process itself truncate the collapse of the entire molecular cloud into a myriad of stars. Hence, more than half of the system's mass might have been ejected. This would have induced the gravitational unbinding of the central stellar system, with subsequent migration of its stars and GCs into the halo, a 'popping' proto-Galaxy, only to be retained within the confines of the dark-matter potential.

The downsizing of clusters over time is intriguing, and suggests that even the extremely metal-poor halo stars might have formed in a few superclusters which quickly disintegrated and dispersed, possibly as a result of dramatic mass loss due to winds and SNe (especially if the IMF was top-heavy). A single 'hyper'-cluster would be less consistent with the large star-to-star variations seen at $[\text{Fe}/\text{H}] < -2$ dex between r- and s-process enrichment.

A second phase of gas accretion, possibly resulting from the previously ejected gas cooling and falling back, might then have given rise to the rapid formation of the bulge and bulge GCs in the nucleus of the fledgling Galaxy. This was probably also accompanied by quick relaxation, given the current kinematics, but not as violent as the initial phase. These two phases might have coincided with, or indeed caused, two distinct epochs of re-ionization of the Universe. The disc formed after that, in a milder manner, and in fact is still seen to be accreting from the halo and satellite galaxies and forming stars throughout at $4 M_{\odot} \text{ yr}^{-1}$.

(d) *Extragalactic populations of star clusters*

Other galaxies may offer different environments and histories in which to study star clusters and their chemical evolution (cf. Harris 2010). The most accessible of these, the Small and Large Magellanic Clouds (SMC and LMC, respectively), have formed stars and clusters for much of their lifetimes and continue to do so. The metallicities of the young and intermediate-age clusters are lower than of those in the Galactic disc by factors of ≈ 2 -3 (LMC) and ≈ 3 -10 (SMC). In the SMC, populous clusters are found at ages of ≈ 6 -7 Gyr (and younger). In the LMC, similar clusters are found, but not in the 4-10 Gyr interval. This has been linked to either a lull in cluster formation or more effective cluster dispersal in the LMC compared to the SMC.

The oldest SMC cluster (and its only GC), NGC 121, already has a metallicity $[\text{Fe}/\text{H}] \approx -1.2$ dex, but then chemical enrichment was slow and only ramped up by a factor of ~ 3 in the last few Gyr (Parisi *et al.* 2009). Others found a more gradual enrichment, which seems more plausible given the properties of the populous clusters of ~ 6 Gyr old. Piatti *et al.* (2007) argued for a different chemical evolution of clusters and the field in the 4-10 Gyr period, but how this would work is not clear. The Da Costa & Hatzidimitriou (1998) and Parisi *et al.* (2009) data possibly suggest a dip in metallicity around 4 Gyr ago, which is also seen in the field (Harris & Zaritsky 2004). Could this be due to the accretion of metal-poor gas from the circumgalactic environment, and could this have triggered enhanced cluster formation in the LMC since then? Hints at a similar formation of clusters in the

Magellanic Clouds from metal-deficient gas in the past 10^8 yr was discussed in van Loon *et al.* (2005). Noël *et al.* (2009) found a monotonic age–metallicity relation, although they confirm earlier findings of recent (past few 10^8 yr) star-formation activity possibly related to an LMC–SMC encounter. They do not find an old halo surrounding the SMC. Although consistent with the existence of just one GC, it begs the question as to what caused the metallicity to start at $[\text{Fe}/\text{H}] \sim -1.5$ dex?

The intermediate-age cluster NGC 419 in the SMC is at a distance of 50 kpc, i.e., 10 kpc in front of the main stellar body of the SMC (Glatt *et al.* 2008), and it has a velocity of 188 km s^{-1} (Dubath *et al.* 1997). This is more than for any SMC cluster in Parisi *et al.* (2009) and closer to that of the LMC ($\sim 200\text{--}300 \text{ km s}^{-1}$). The similarity in age, metallicity and the properties of its evolved giant stars to the LMC cluster NGC 1978 was noted in van Loon *et al.* (2008). Only intermediate-age clusters are seen around that distance in front of the SMC. The older clusters concentrate around 60 kpc (Glatt *et al.* 2008). A link between these intermediate-age clusters and an origin (of the clusters or the gas they formed from) in the LMC is tempting.

The Andromeda spiral galaxy (M 31) also harbours populous intermediate-age clusters (Barmby *et al.* 2009), besides a bimodal GC system that differs from that of the Milky Way in detail (Galleti *et al.* 2009). Several dwarf galaxies in the Local Group have one or a few (old) GCs associated with them (cf. Strader *et al.* 2003). Further afield, the GC systems of large elliptical galaxies are generally found to have bimodal distributions of colours and metallicity indices, possibly analogously to the Galactic halo and bulge populations. The bimodality has been interpreted as due to a past major merger, but there is little direct evidence supporting this scenario. One might ask why only one major merger occurred, and not two, or three. Perhaps more systematic investigations of the properties of GC systems as a function of host-galaxy type will offer answers.

4. The end of a paradigm: clusters as composite systems

Discoveries of dispersion in the colours of giant branches and star-to-star variations in abundances of N, Ca, etc., already indicated that stars in Galactic GCs do not have identical composition. That this might be caused by differences in age and primordial enrichment has been validated in recent years by accurate photometry and spectroscopic confirmation in a growing number of GCs, revealing not only dispersion in stellar properties but also separate, discrete populations. Although so far found in massive GCs, this is no longer the exclusive property of the peculiar, most massive GC, ω Centauri (cf. McDonald *et al.* 2009). A summary is presented in Table 1, roughly in order of decreasing confidence and cluster mass, M .

The evidence for multiple populations roughly falls into three main categories: (1) multiple subgiant branches generally indicate discrete formation epochs separated by a measurable delay, (2) multiple MSs indicate most likely differences in He abundance, possibly without the large delays seen in the subgiant-branch splitting, and (3) a spread in chemical properties of the stars may be due to an extended period of star formation and continuous chemical enrichment. The distribution over chemical properties may also show discrete populations. The presence or absence of subgiant-branch splitting can then constrain the delay in enrichment between these populations.

Table 2. *Galactic clusters (possibly) containing multiple populations.*

Cluster(s)	bulk [Fe/H]	M ($10^6 M_{\odot}$)	Populations	Remarks
<i>Splitting of the main sequence</i>				
ω Cen	-1.6	3	≥ 3 over 3 Gyr	Fe spread
NGC 2808	-1.2	1	3 within 1 Gyr	
<i>Splitting of the (sub-)giant branches</i>				
M 54	-1.6	2	2	Sgr dSph nucleus?
NGC 6441	-0.5	2	2	$\Delta Y \sim 0.1$?
NGC 6388	-0.6	1	2	
M 22	-1.6	0.6	2	Fe spread
NGC 1851	-1.2	0.5	2	$\Delta Y \sim 0$?
M 4	-1.2	0.2	2	bimodal O and Na
<i>O–Na anticorrelation</i>				
all	-2.3 to ~ 0	~ 0.01 to 3	spread (in age?)	increases with M
<i>N abundances</i>				
all?	-2.3 to ~ 0	~ 0.01 to 3	often bimodal	
<i>Horizontal-branch morphology ('second parameter')</i>				
all?	< -1 ?	~ 0.01 to 3	unclear	not primordial?
<i>White-dwarf luminosity function</i>				
NGC 6791	+0.4	> 0.004	2 ($t \approx 8$ Gyr)	spread in Na? (He?)

(a) ω Centauri: a freak?

The photometric detection of discrete populations in the colour–magnitude diagram (CMD) of the most massive Galactic GC, ω Cen (Lee *et al.* 1999) added complexity to the hypothesized star-formation history giving rise to the spread in metallicity (from $[\text{Fe}/\text{H}] \approx -1.7$ to ≈ -1.2 dex), O–Na anticorrelation, and metallicity-correlated s-process enhancement observed by Norris & Da Costa (1995) and Smith *et al.* (2000). These authors had suggested an extended period of star formation (≈ 2 Gyr), with the metal-richer stars forming from material enriched by massive stars ($> 8 M_{\odot}$; α and Fe-peak elements) and eventually also by contributions from intermediate-mass AGB stars (≈ 1.5 – $4 M_{\odot}$; heavy s-process elements). After having identified a sparse ($\approx 5\%$ of all stars), particularly red and dim branch off the main RGB, Pancino *et al.* (2000, 2002; see also Origlia *et al.* 2003) proved that this ‘anomalous’ RGB-a is the metal-richest population (up to $[\text{Fe}/\text{H}] \approx -0.5$ dex) and has lower $[\alpha/\text{Fe}]$ and higher $[\text{Cu}/\text{Fe}]$ ratios indicative of SN Ia enrichment. Stanford *et al.* (2007) obtained spectroscopic abundance measures in MS stars, which are unaffected by internal processes. They confirmed a 2–4 Gyr formation period with a monotonic age–metallicity relation, and that the C, N and Sr enhancements are primordial (with N enhanced in metal-richer stars; cf. Kayser *et al.* 2006). Thus, a simple, sequential chemical-enrichment scenario emerges.

Meanwhile, complications had arisen. A double MS had been discovered (Anderson 1997; Bedin *et al.* 2004). Piotto *et al.* (2005) then provided spectroscopic evidence showing that the blue MS corresponds to the intermediate-metallicity population ($[\text{Fe}/\text{H}] \approx -1.2$ dex), but the red MS corresponds to the dominant metal-poor population ($[\text{Fe}/\text{H}] \approx -1.7$ dex). This could only be explained if the intermediate-metallicity MS stars were He-enriched by $\Delta Y \approx 0.14$! (Curiously, the metal-richest population may be He-normal.) Piotto *et al.* suggested that most of the SN ejecta from the metal-poor population must have left the system, leaving

less massive stars to create the chemical imprint upon the intermediate-metallicity population.

Recently, Johnson *et al.* (2009) distinguished *four* populations, the intermediate-metallicity population splitting up into slightly metal-richer ($[\text{Fe}/\text{H}] \approx -1.05$ dex) and more metal-deficient ($[\text{Fe}/\text{H}] \approx -1.45$ dex) subpopulations. They found that, of the metal-poor stars ($[\text{Fe}/\text{H}] < -1.2$ dex), about half formed from Type II SN ejecta (similar to disc and halo field stars) but the other half are also enriched in ejecta from $\approx 4\text{--}8 M_{\odot}$ AGB stars. The majority of metal-rich stars ($[\text{Fe}/\text{H}] > -1.2$ dex) appear to have formed largely from AGB ejecta. They further suggested that large values of $[\text{La}/\text{Eu}] > +1$ dex (accompanied by Ba enhancements) indicate that $\approx 25\%$ of stars are affected by binary mass transfer (none of the most metal-poor stars, and more at higher metallicities). Although these observations can only be explained with a prolonged formation history, the mildness of Type Ia SN enrichment favours shorter (≈ 1 Gyr) rather than longer (≈ 4 Gyr) timescales.

These four groups relate to those identified in a comprehensive compilation of data on the MS, subgiant branch and RGB by Villanova *et al.* (2007). They traced the $[\text{Fe}/\text{H}] \approx -1.1$ dex population into the red MS. However, the brightest (faintest) subgiant branch belongs to the metal-poor (metal-rich) population. If, following Villanova *et al.*, these are interpreted as measures of age, then conventional models would assign younger ages to the metal-poor stars and older ages to the metal-rich stars. Villanova *et al.* remained uncertain about the metal-richest ($[\text{Fe}/\text{H}] \approx -0.6$ dex) stars on the RGB-a, and there appears to be an additional (fifth) intermediate subgiant branch which is difficult to link to just one of the components discussed. They arrive at a rather curious picture for the make-up of ω Cen:

- The oldest stars (12–13 Gyr) belong to a trace population ($\approx 10\%$) of metal-rich ($[\text{Fe}/\text{H}] \approx -1.1$ dex) stars;
- Stars of similarly old age, possibly slightly younger (12 Gyr), belong to an $\approx 20\%$ population of metal-poor ($[\text{Fe}/\text{H}] \approx -1.7$ dex) stars;
- A much younger population (9–10 Gyr), $\approx 30\%$ of the total MS population, consists of considerably He-enriched, intermediate-metallicity ($[\text{Fe}/\text{H}] \approx -1.4$ dex) stars;
- The youngest stars (9 Gyr) belong to the dominant ($\approx 40\%$), metal-poor ($[\text{Fe}/\text{H}] \approx -1.7$ dex) population.

Or can these inferred age differences be brought back to within $\ll 1$ Gyr by allowing for variations in the sum of C+N+O and/or He content?

(b) *Other clusters: a trend?*

Also a massive GC, NGC 2808 has revealed three of its MSs, which probably formed well within a Gyr (Piotto *et al.* 2007). This GC is interesting as it has been associated with a stellar overdensity in the halo, possibly the debris of a disrupted dwarf galaxy. It is also one of the few coincidences with an HI cloud, of $\approx 200 M_{\odot}$ (Faulkner *et al.* 1991), although the association is uncertain.

Multiple (two) subgiant branches have been found in NGC 1851 (Milone *et al.* 2008), another massive GC and one with both an extended blue HB and a red

clump. It is tempting to relate these two groups of core-He-burning giants to each of the two subgiant branches and hence to populations of different age. No split of the MS has been revealed to date, suggesting that no He enrichment took place between these two star-formation epochs. Ventura *et al.* (2009) and D’Antona *et al.* (2009) argued, however, that the age difference is not real, but mimicked by an enhancement in the sum of C+N+O. They held AGB stars responsible for this, as a correlation is observed with Na, Al, Zr and La (Yong *et al.* 2009). It would still be simplest to explain an enriched population as one that formed subsequently, i.e., after some delay, but this delay may be small (\ll Gyr).

Splitting of the subgiant branch has been observed in M 54, M 4, the metal-rich GCs NGC 6388 and NGC 6441, and also in M 22 (Marino *et al.* 2009), known to exhibit a spread in [Fe/H] (Da Costa *et al.* 2009). Caloi & D’Antona (2007) explained the HB morphology of NGC 6441 by invoking He enrichment by ≈ 0.1 dex, but no splitting of the MS has been observed. In M 3, on the other hand, the distributions of RR Lyrae (HB pulsators) and other HB-morphology aspects suggest something intricate, but the He spread is constrained to < 0.01 dex (Catelan *et al.* 2009), and no evidence of multiple populations has been found in CMDs of M 3. The question of He enrichment, like that of C+N+O enrichment, is therefore still open. The two subgiant branches discovered in M 4 by Marino *et al.* (2008) may be related to the bimodal O and Na distribution observed in that cluster, with the O-depleted stars also being CN-rich (suggesting enrichment by AGB stars experiencing HBB).

One can be bold, and proceed to explain *all* oddities observed in GCs as due to multiple populations (in the sense of them being formed in distinct events, either in time, place or both). Is the ‘second parameter’ (§3b) related not just to a difference in age between GCs, but also to the possible presence of a second population within a given GC, explaining GCs that exhibit both a red and blue HB? Is the O–Na anticorrelation caused by stars that occupy different places on that sequence having formed at slightly different times and thus sampling slightly different chemical enrichment (or dilution)? The supersolar metal-rich cluster NGC 6791—‘almost’ a GC—appears to harbour two populations of WDs (Kalirai *et al.* 2007): could this also be related to the cluster having formed stars twice? NGC 6791 seems chemically homogeneous, except possibly for a spread in Na (Carretta *et al.* 2007b). Could this be related to differences in He content, perhaps explaining its He WDs? Then again, some GCs lack evidence for a composite nature, e.g., NGC 6397.

Galactic OCs show no O–Na anticorrelation. They all have roughly solar [O/Fe] and possibly somewhat higher [Na/Fe] than the primordial component of the O–Na sequence. [O/Fe] in these clusters decreases with increasing [Fe/H] as in the disc field stars (De Silva *et al.* 2009), simply due to the build-up of Fe from Type Ia SNe. Young clusters do not display any chemical inhomogeneities (D’Orazi & Randich 2009), so there is a fundamental difference between the formation of OCs and that of GCs, which display a composite nature.

The Magellanic Clouds offer an interesting testing ground for examining the possible origins of the composite Galactic GCs. No composite GCs have been uncovered, but it was claimed that some intermediate-age (~ 2 Gyr) populous clusters have additional populations up to 300 Myr younger: NGC 1846, NGC 1806 and NGC 1783 in the LMC (Mackey *et al.* 2008), and perhaps more similar clusters (Milone *et al.* 2009a). This has now been shown to likely result from a spread in stellar rotation rates (Bastian & de Mink 2009). Although the CMDs of the affected

clusters look suspiciously similar to those of Galactic composite GCs, the effects of rotation only show up in the small mass range that happens to be comprised by the populous intermediate-age Magellanic clusters, also naturally explaining the lack of ‘multiple populations’ in both younger and older Magellanic Cloud clusters.

(c) *The origin of the mixed composition of Galactic globular clusters*

The abundance spreads and patterns provide ample evidence for a continuous range in stellar content of Galactic GCs, most easily interpreted as due to an extended period of formation. For several progressively metal-richer populations in ω Cen, the successive contribution by less massive AGB stars is seen, for instance, in the growing enhancement of Na at similar relative Fe-peak abundances and α /Fe ratios originating from the early contribution from Type II SNe (Johnson *et al.* 2009). The ubiquitous Na–O anticorrelation must also have been established during cluster formation (Carretta *et al.* 2007a). Field stars, which do not span an O–Na sequence, show supersolar [O/Fe] at slightly subsolar [Na/Fe], identical to the corresponding locus in the O–Na sequence of Galactic GCs (Carretta *et al.* 2009a; cf. Gratton *et al.* 2001). Na is followed by N, and both the primordial and extreme ends of the O–Na sequence are more populous in more massive GCs (Carretta *et al.* 2009a,b). In massive GCs, stars may have formed over a longer period of time and consequently also from gas enriched by lower-mass ($< 10 M_{\odot}$) stars.

Enrichment of molecular clouds by massive stars on a timescale of ~ 10 Myr has been invoked to explain the difference in metallicity between the youngest and ~ 10 Myr-older stars in the Orion star-forming region (Cunha & Lambert 1994). But D’Orazi & Randich (2009) find 30–55 Myr-old OCs to be chemically homogeneous to within a few percent. Galactic OCs do not show CN bimodality, an O–Na sequence or multiple populations. In the 30 Doradus mini-starburst in the LMC, multiple populations are seen, including a few Myr-old, few $\times 10^4 M_{\odot}$ cluster, R 136. But there is no evidence that the cluster will develop into one with multiple populations of different age and metallicity. Neither is there any sign of populous intermediate-age clusters in the Magellanic Clouds gaining an additional population of younger, metal-richer stars. The fact that multiple populations are only seen in old, possibly preferentially massive, clusters may mean it is intimately related to the unique conditions under which stars formed in the early history of the Galaxy, probably in a dense medium near the centre of the proto-Galaxy.

The chemical differences among discrete multiple populations within individual Galactic GCs are several tenths of a dex, suggesting bursts of star formation or other individual events. Some of these bursts are confirmed, by direct age estimates, to be more than a Gyr apart. The age resolution in > 10 Gyr-old GCs is insufficient to reveal populations that differ by less than several $\times 10^8$ yr, which is an order of magnitude longer than the lifetime of a molecular cloud, and sufficient for stars with birth masses of $> 3 M_{\odot}$ to have evolved and chemically enriched the local ISM. There are probably easier ways of producing subpopulations that only differ by a few Myr in age and little or nothing in metallicity, than forming a cluster, letting it mature for one or two Gyr, before, somehow, supplying it with newly-formed stars. For such extensive age differences, one needs to invoke the GC having remained part of a larger system which was gas-rich for at least a few Gyr since the GC formed, or for two independently formed GCs to have merged.

(i) *Composite clusters as a result of mergers*

The velocity dispersion of the GC system is large, and dynamical friction is not given much chance to convert velocity differences into internal kinematic heat: GCs would simply pass through each other with rather minor consequences. In the formation stages, when peculiar velocities are $\sim 1 \text{ km s}^{-1}$, mergers of two GCs are more plausible. But then, one would expect the GCs to be of very similar age and composition. Pancino *et al.* (2007) found a similar rotation rate for all populations in ω Cen, and no radial differences were found in NGC 1851 (Milone *et al.* 2009b). Memory may have been erased through dynamical evolution of the merged system, or mergers take place preferentially involving systems that share similar kinematics (possibly increasing the effectiveness of dynamical friction, for instance, in co-rotating systems as opposed to counterrotating systems), or there never was a merger.

Mergers do not explain an extended period of enrichment either, only possibly a secondary population, while a third population, i.e., a third merger, would be highly unlikely. If one could separate the primary and secondary populations, they would not each look like GCs in their own right, certainly not the secondary population (there are no solely N-rich clusters).

(ii) *Self-enrichment*

Self-enrichment is an attractive scenario to explain abundance patterns which are only seen in GCs and not in the field, but how viable is it? If not through their fast winds, the SN deaths of massive stars surely remove ISM from the GC. But the winds of intermediate-mass stars are much slower, in particular in metal-poor systems, and within the escape velocity of massive, compact GCs. Could the AGB ejecta on their own have formed the next generation of stars? Remember that perhaps as much as half of the stellar content of massive Galactic GCs might have formed in subsequent epochs (cf. ω Cen, NGC 6441, M 22, NGC 1851).

One can easily estimate that stars in the mass range $2\text{--}8 M_{\odot}$ yield about half as much mass in the form of ejecta as there would be in stars in the approximate mass range $0.3\text{--}0.8 M_{\odot}$. To form stars from this at about the maximum efficiency, $\sim 20\%$, would thus generate a second generation of stars of about 10% in number compared to the first generation (cf. Yi 2009). To form an N-enriched population similar or greater in number than a co-existing, N-poor(er) population would push this scenario to its limits: it already comprises a generous range in AGB stars and as a consequence also a Gyr age difference.

Accreted gas may add to AGB ejecta within the GC before forming stars. Indeed, Ventura & D'Antona (2009) confirm that AGB ejecta must be diluted by pristine gas to reproduce the O–Na anticorrelation. The additional gas may come from the massive stars in the same generation of AGB polluters (in which case it would also be enhanced in Fe-peak, α and r-process elements), or it may be remnant gas from which that GC population had formed in the first place. Alternatively, it may come from elsewhere, in which case the enrichment of the second generation of stars would bear no relation to that of the first generation. While this might help explain the strange temporal and chemical ‘order’ of the subpopulations in ω Cen, it disagrees with the absence of star-to-star variations in Fe content in most GCs.

A further challenge for the self-enrichment scenario is that clusters do not remain gas-rich for long, so it is difficult to envisage AGB ejecta to accumulate within the cluster over a Gyr or so. No gas-rich clusters are known except very young ones, and even then the gas usually surrounds, rather than permeates, the cluster. In young clusters, SNe—if not fast stellar winds—drive out the gas. Old clusters have little gas, if any, too, despite having had long to produce it. Interaction with Galactic halo gas is a likely removal mechanism (van Loon *et al.* 2009). So, multiple populations in GCs are likely to have arisen not from gas accumulation but from gas accretion, probably quite suddenly in the form of a cooling flow (cf. Bekki & Norris 2006). This is corroborated by the central condensation of the metal-rich subpopulations in ω Cen (Bellini *et al.* 2009). This explains the variety of GCs and the difficulty to present a unified chemical evolution picture for all GCs.

It has been suggested that nonconservative mass transfer in massive binaries could provide enough interstellar gas for subsequent star formation, and that this gas is enriched in He, N, Na and Al and depleted in C, O and Mg (de Mink *et al.* 2009). Although this can explain some of the chemical-abundance patterns found in GCs, the majority of massive stars must participate in this scenario for it to contribute significantly and it does not explain Gyr delays in star formation.

(iii) *Did globular clusters originate in dwarf galaxies or dark-matter mini-haloes?*

ω Cen, with its retrograde orbit, was suggested to be the nuclear remnant of a dissolved dwarf spheroidal (dSph) galaxy. M 54 is, in fact, a massive GC at the heart of the Sgr dSph, which is currently being disrupted in spectacular fashion. Attempts to build a chemical evolution model based upon this scenario invoke a $10^8 M_{\odot}$ system, of which 1% survives in the form of the present-day GC (Bekki & Freeman 2003; Romano *et al.* 2009). The attraction of a more massive stellar system as the birthplace of GCs is that the deeper gravitational potential could retain more ejecta, but also that these ejecta could come from a larger population of stars that never did nor will form part of the GC. Self-enrichment scenarios indeed require the GC to be embedded in a larger system (Renzini 2008). The preferential loss of low-mass, older stars in the early dynamical phases could then also have caused the comparatively large remaining further-enriched populations (D’Ercole *et al.* 2008).

But there are problems with this origin: dSph galaxies show different abundance patterns (Geisler *et al.* 2007): the r-process is relatively more important in dSphs. Several other GCs in addition to M 54 are associated with the Sgr dSph, also showing chemical inhomogeneity: where did they get that from, if they are not nucleated? If all GCs had formed in dSph galaxies, enough stars would have been shed to supply the halo and disc with most of their present stars. This is clearly not the case for the more enriched disc. The central concentration of the bulge GCs is also inconsistent with minor mergers and perhaps the result of star formation triggered by a major merger (Griffen *et al.* 2009).

It has also been suggested that the very distant (~ 100 kpc) GCs might have originated elsewhere, for instance, the metal-poor, spatially very extended GC NGC 2419 (van den Bergh & Mackey 2004) in which Ripepi *et al.* (2007) find no spread in metallicity and no spread in the branches, except an extended HB. MGC 1, a very remote GC in the M31 halo, may be similar (Mackey *et al.* 2009). Pal 3 looks like an archetypal GC, with abundance patterns similar to many other

GCs, but different from those in dSph galaxies (Koch *et al.* 2009). Curiously, the $\sim 10^8 M_{\odot}$ required for the formation and self-enrichment of ω Cen is similar to the potential total mass associated with Pal 4 and its HI cloud (van Loon *et al.* 2009). Could the putative larger systems within which GCs formed be largely dark? A ‘halo’ has been discovered around NGC 1851 (Olszewski *et al.* 2009): could it have a dark-matter halo too? Could dark-matter haloes be the cause of the large extent of NGC 2419 and MGC 1? Griffen *et al.* (2009) show that the distant GCs may indeed have kept dark haloes. (GC dark haloes may only become noticeable beyond the standard tidal radius.)

5. Epilogue

In the briefest of summaries, one might say that above a certain mass (of the molecular cloud from which it formed, or perhaps rather of an associated dark-matter component) the formation of a cluster takes enough time for chemical enrichment to take place during the formation of subsequent generations of its stars. Such clusters foremostly probe the conditions of their formation. At lower masses, clusters are formed essentially instantaneously as a single, homogeneous population. Such clusters are more unique probes of the star-formation and chemical-enrichment history of their host (taking into account cluster dynamics and dispersal).

To make progress, more complete abundance measurements (He!) are needed, preferably in MS stars (not He), also in the less massive and more distant GCs and especially the metal-poor ones to make a more direct connection to the formation of the halo. The interpretation of such measurements remains problematic: more precise age determinations are needed, distinguishing formation epochs within GCs and between GCs differing by $\ll 1$ Gyr. Also, yields of individual elements are not reliable in the quantitative detail needed to reconstruct the rapid formation of old Galactic GCs.

Soon, clusters in dwarf and spiral galaxies throughout the Local Group will be subjected to similar chemical analysis as Galactic clusters have been, both through photometry and spectroscopy. Environments may become accessible which resemble the conditions in which the Galactic GCs we see today were formed, such as those of interacting galaxies, both nearby and high-redshift (hence historic) starbursts and star-forming galaxies with ISM metal deficiencies typical of Galactic GCs, for instance I Zw 18.

As we find that we cannot measure directly what happened in the past, or that there are too few clusters with which to describe their population, we may need a theoretical framework to constrain the freedom of our imagination. (This may take the form of the ever more realistic models of cluster and galaxy formation.)

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